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REPORT TO OFFICE OF NAVAL RESEARCH

PROGRAM: SBIR 89-1 CONTRACT: N00014-89-C-0230

INNOVATIVE TECHNIQUES FOR THE PRODUCTION OF LOW COST 2D LASER DIODE ARRAYS

May 1990

FINAL REPORT

Prepared by Northeast Semiconductor, Inc.

The objective of this program was to develop a low cost fabrication method for high performance laser diode arrays. The program focussed on reliable and cost-effective ways to grow, assemble and test diode bars of MBE material.

Quantum-well laser structures (GRINSH-SQW) were grown on 2" and 3" GaAs substrates. These wafers were photolithographically processed, scribed into bars, and the bars assembled by various techniques. The assemblies were tested for performance, reproducibility, and reliability.

The originally proposed assembly, a grooved BeO block, was evaluated and abandoned as unreliable. However, a simplified bar and individual BeO substrate assembly method was developed, and state of the art results achieved on robust 1 cm linear diode arrays, which survived repeated high power testing to power level in excess of 80 watts/bar. This method may be scaled up for multiple bar assemblies without additional complexity by adding laser bars and BeO spacers as required. The BeO sub-mounts are coated prior to assembly in such a fashion to provide a low resistance series connection to each bar in the array, similar to the grooved substrate series connection geometry.

The extension of this assembly method in a phase II program will combine many of the advantages of the "Array in a Groove" technique with the more conventional "Rack & Stack" approach. The phase I program objective has essentially been met on linear 1 cm laser bar assemblies. A reproducible array fabrication process has emerged which can be scaled up to low cost 2D arrays in the near future.

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I. Introduction/Phase I Objective

The phase I program of Northeast Semiconductor Inc. (NSI), SBIR contract N00014-89-C-0230, entitled "Innovative Techniques for the Production of Low Cost 2D Laser Diode Arrays" is briefly described. The emphasis at the outset of this program was to develop a low cost assembly method for high performance laser diode arrays. Early in this program, the originally proposed assembly method was abandoned as it suffered with many technological problems which out weighed its potential advantages. However, a simplified, single bar assembly method was pursued and state of the art results are achieved on robust 1 cm linear diode arrays (those devices which survive repeated high power testing). The extension of this assembly method in a phase II program will combine many of the advantages of the old "Array in a Groove" technique with the more conventional "Rack & Stack" approach. Also, NSI considerably improved its array test capability as is demonstrated by the near field patterns, the PI curves and array spectra presented in this report during the phase I program. Lastly, progress was made on facet coating of laser bars with dielectric stacks during phase I, however, coated bars have not yet been used in array assemblies. The phase I program objective has essentially been met on linear 1 cm laser bar assemblies. A reproducible array fabrication process has emerged which can be scaled up to low cost 2D arrays in the near future.

II. Changes in Array Assembly Process

The array assembly techniques investigated in phase I are described in this section. The problems with the originally proposed fabrication techniques are highlighted and justification for selecting new and improved methods for assembly are given.

A. Old Method - Bar in a Groove Concept

When this SBIR phase I proposal was submitted, NSI was pursuing a novel grooved substrate approach for array assembly which is schematically depicted in figure 1. The concept of placing a diode bar in a groove is at first glance an attractive one, however, several factors led to NSI's decision to discontinue effort on this approach: i) the saw cut grooves in the BeO backplane are irregular with non parallel surfaces due to erosion of the diamond saw blade during fabrication, ii) the grooved backplane requires very tigh tolerances on laser bar thickness (± 10 μm) which creates processing constraints on the diode bars which are difficult (costly) if not impossible to meet, iii) the bowing present in the laser bars result in high yield loss in the assembly during the insertion of the bar into the groove from breakage, and iv) the only method which has been successful in placing solder between the backplane and the diode bar utilizes a corrosive flux/soft solder scheme. The combination of these problems make array assembly lack reproducibility. Presumably due to the lack of control of the solder wicking into the grooves excess solder accumulates behind the diode bar (adjacent to the rear facet) and eventually shorts that bar in the assembly. *NSI has fabricated over 25 - 10 diode bar assemblies by this technique in phase I and not a single assembly has survived the testing without severe degradation or total failure.* The test results given below are taken as carefully as possible prior to the catastrophic failure events.

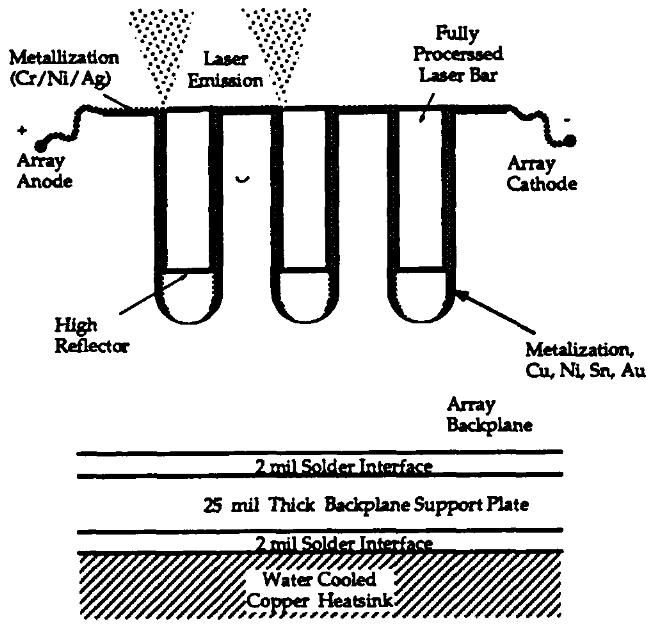

Figure 1. Schematic diagram illustrating a crossectional view the array assembly with a grooved BeO substrate. These devices require the use of soft solders and corrosive flux.

The 2D arrays were prepared by matching 10 slots in the BeO backplane extending the full width of the substrate to the widths of the laser bars. This requires a pre-selection process for bars as each groove dimension varies. The slot dimensions were nominally 100 μm wide and 500 μm deep. Metallization was applied to the top surface and sides of the slots in a thermal evaporator. Two deposition runs were used with the substrates angled at $\pm$ 15 ° to the horizontal enabling the side walls to receive adequate metal thickness without coating the bottom of the slot. Two different metallization schemes were used, Ti/Ni/Au and Ti/Pd/Au. The latter combination demonstrated the most consistent and effective wetting properties with the range of solders used. To assemble the arrays, the substrate is placed on a heating jig and laser diode bars are loaded into the individual slots. Sections of indium alloy solder preform are then placed over the bars and slot areas. A small quantity of indium alloy flux #5-R is then applied. Power is applied to the heating fixture until the temperature is high enough to melt the solder (156 °C for 70 % In/30 % Pb). As soon as melting has occurred and wetting of the laser diode bars is observed, the power is removed and the assembly allowed to cool. In some instances complete wetting of the solder to the diode metallization does not occur. The addition of extra flux and solder did encourage full wetting but this usually required keeping the array at the melt temperature for several minutes. The assembled array is cleaned in trichloroethane and isopropyl alcohol to remove the flux. An additional inspection for complete flux removal is required prior to testing.

Because the BeO grooves' dimensions change the thermal resistance through the soft solder to each diode in the array will vary causing local hot spots in the array. The flux used has been observed to attack the facet coatings which NSI is currently using, relatively standard Al_2O_3/Si reflector. Together these facts suggest that low cost and reliable arrays will not result from this approach. The resulting process requires new facet coating to be developed or different solder fluxes to be used, multiple inspection of BeO backplanes and laser bars prior to and after each assembly.

B. New Method - Bar/Sub-Mount Stacking

The assembly method presently under investigation for the production of low cost diode arrays is shown in figure 2. The assembly procedure for a single bar array is as follows.

1. A BeO slab is cut to a .5″ x .5″ x .025″ dimension and surface ground to a 40 μinch roughness.
2. The ceramic is metalized on one face with Ti/Pd/Au.
3. The BeO is placed on a graphite heater block and positioned so that it's plane is normal to a quartz backing plate.
4. The assembly is heated to 120 °C in forming gas.
5. A strip of 75 % In/30 % Pb solder preform (.001″ × .002″ × .434″ dimensions) is placed on the ceramic.
6. A diode bar is the placed on the solder strip p-side down followed by another solder strip on the n-side while the temperature remains at 120 °C.
7. A .003″ OFHC Cu foil is placed on top of the stack.
8. A 4 oz weight is added and the assembly temperature is increased to 350

°C in 30 seconds and is maintained at temperature for 15 seconds.

9. The array is then clamped tight between two OFHC Cu heat sinks that also serve as the anode and cathode.

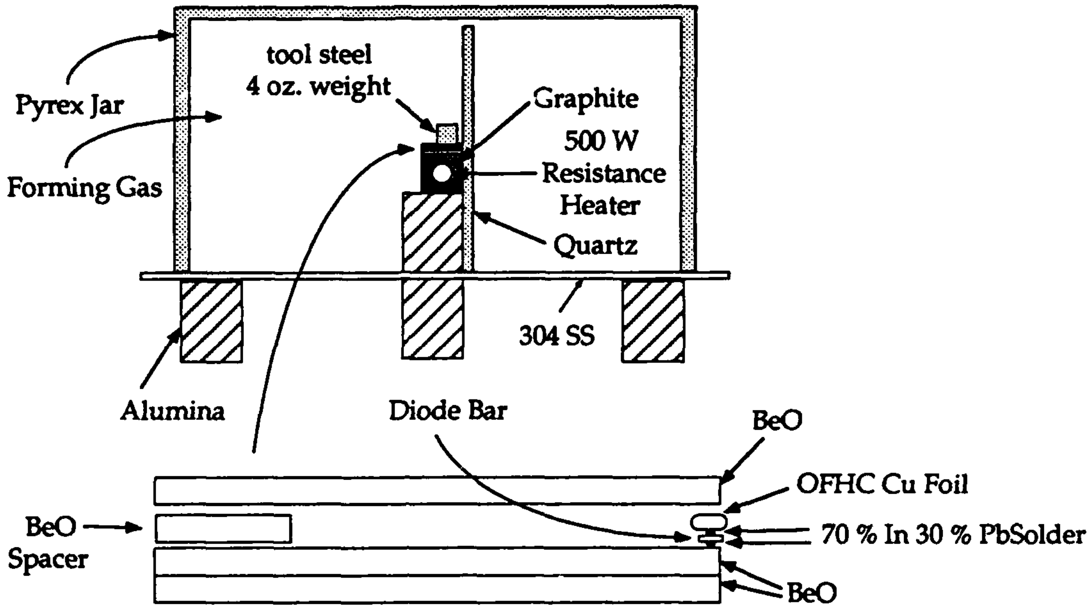

Figure 2. Schematic diagrams describing the new assembly apparatus and process for linear 1 cm bars in their early stages of development. The bar is mounted to a BeO submount and a Cu foil is soldered to the n-side of the diode.

After assembly the linear laser bar appears as indicated in figure 3.

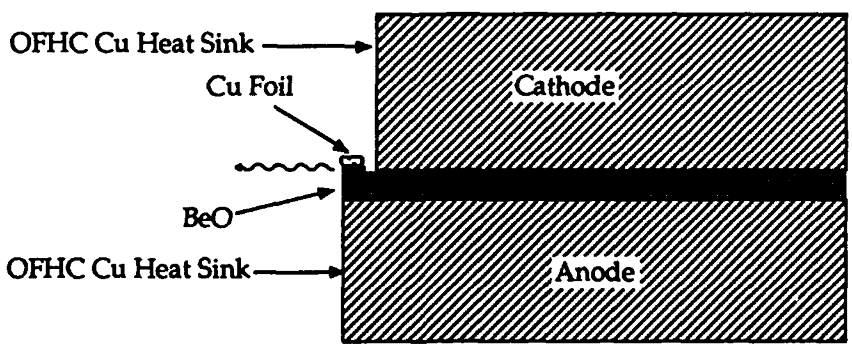

Figure 3. Schematic diagram of the finished 1 cm linear laser bar assembly prior to mounting in the test fixture. The heat sinking is achieved by sandwiching the submount between to Cu heat sinks as shown.

This method has provided NSI with a reproducible source of packaged linear diode arrays. It may be scaled up for multiple bar assemblies without additional complexity by adding laser bars and BeO spacers as required. The BeO sub-mounts are coated prior to assembly in such a fashion to provide a low resistance series connection to each bar in the array, similar to the grooved substrate series connection geometry.

III. Test Results on 2D Arrays via the Old Method

A series of array test data is given in this section on the 10 bar arrays fabricated with the grooved substrate approach. These results represent the best performance obtained prior to degradation. First, consider the best PI data obtained on such an assembly shown in figure 4.

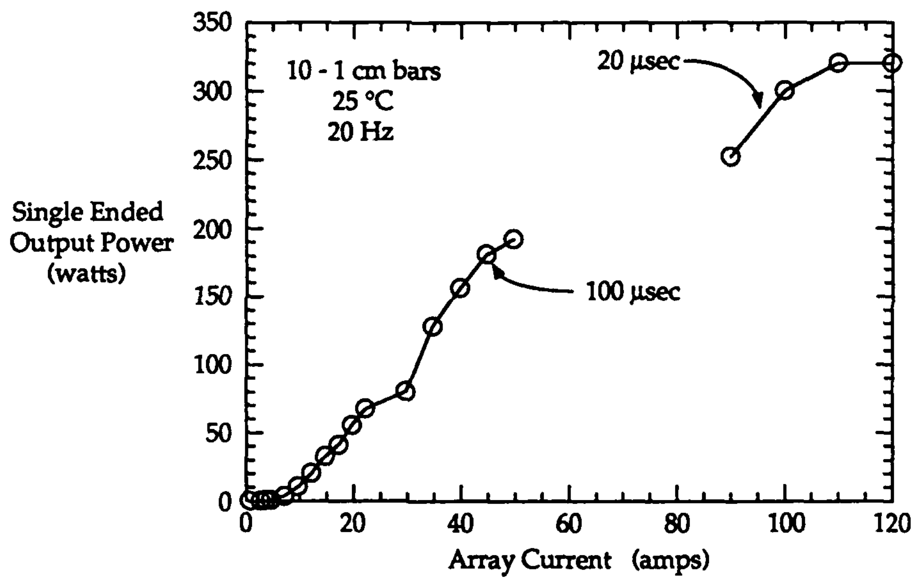

Figure 4. Power versus current relationship measured on the highest power 2D array assembly prior to blowout. The 20 μsec data was obtained first at high current levels followed by the 100 μsec observed right up to catastrophic failure. The heat sink temperature is given in the figure.

A lower power assembly survived the spectral characterization which is shown in figure 5. In this device a narrow emission bandwidth was observed at drive levels close to threshold as shown in the lower spectrum. The emission wavelength and bandwidth was 794 and 3 nm, respectively. At higher current levels (12 amps) the spectrum broadens significantly (FWHM $\approx$ 10 nm) and shifts to longer wavelengths due to non-uniform heating of the array. These results are typical of all 2D array assemblies tested. It is believed that the varying groove dimensions in the BeO creates thermal non-uniformity in sections of the array. In spite of these results at low currents, uniform near field images are observed on portions of these arrays.

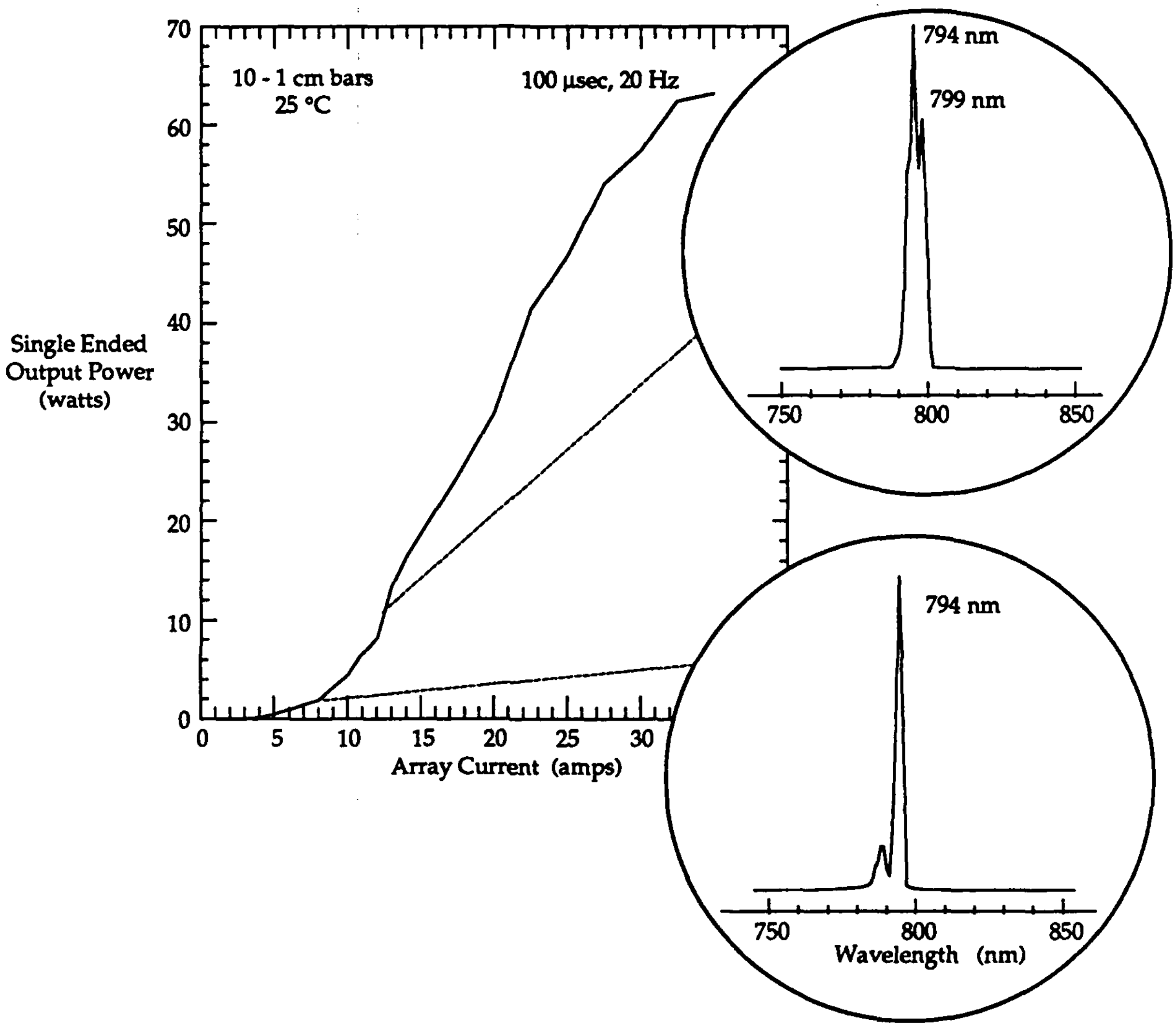

Figure 5. Power versus current relationship and emission spectra of a 2D, 10 bar assembly taken at 100 μsec pulses at 20 Hz.

The amount of wavelength shift associated from heating was obtained by measuring the peak emission wavelength at fixed current levels while changing the pulse width (duty cycle). These results are shown in figure 6. As the pulse widths change from 10 to 100 μsec the emission wavelength shifts roughly 6 nm as shown. This corresponds to a 12 meV change in the photon transition energy yielding a junction temperature rise of approximately 30 °C. It should be noted that short pulse data (1 μsec) on the laser bars prior to packaging yield a peak emission wavelength of 787 nm. This represents a relatively severe rise in temperature for such modest drive currents and is indicative of a poorly heat sunk array. The spectral broadening indicates the presence of hot spots in the array. These results do not compare to those observed on the linear assemblies. For example, the linear bars assembled with the new method show less than 0.5 nm shift at 3 times threshold ($\approx$ 30 amps) by changing the pulse width from 10 to 100 μsec indicating superior heat sinking.

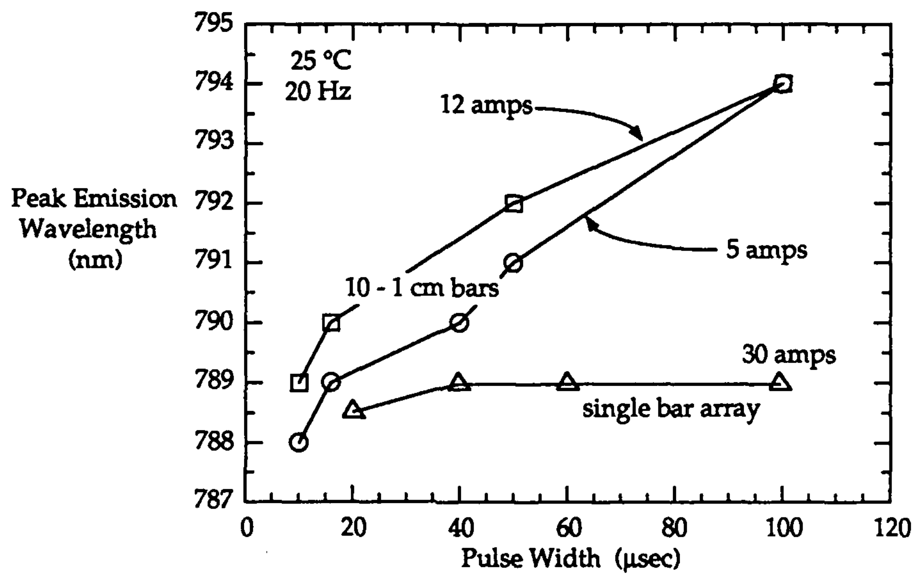

Figure 6. Peak emission wavelength plotted verses pulse width for the same array whose PI curve appears in figure 5. The current level for each set of data is indicated in the figure. For comparison data is included on a linear array assembly fabricated by the new method.

The near field image of the same 2D array operating at 15 amps is shown in figure 7. Non-uniformities are evident in this data, but the majority of individual lasers are emitting. In this image the camera has reached saturation which obscures the emission uniformity or lack there of. NSI has the ability to analyze these near field images and produce meaningful profiles of such data provided the camera has not reached saturation. Consider the near field pattern of a portion of a 2D array containing 12 separate emitters is given in figure 8. Good uniformity of emission intensity is exemplified here, over a limited number of individual emitters. This type of measurement data is primarily useful in qualifying array assembly practices and can be applied over the entire emission aperture.

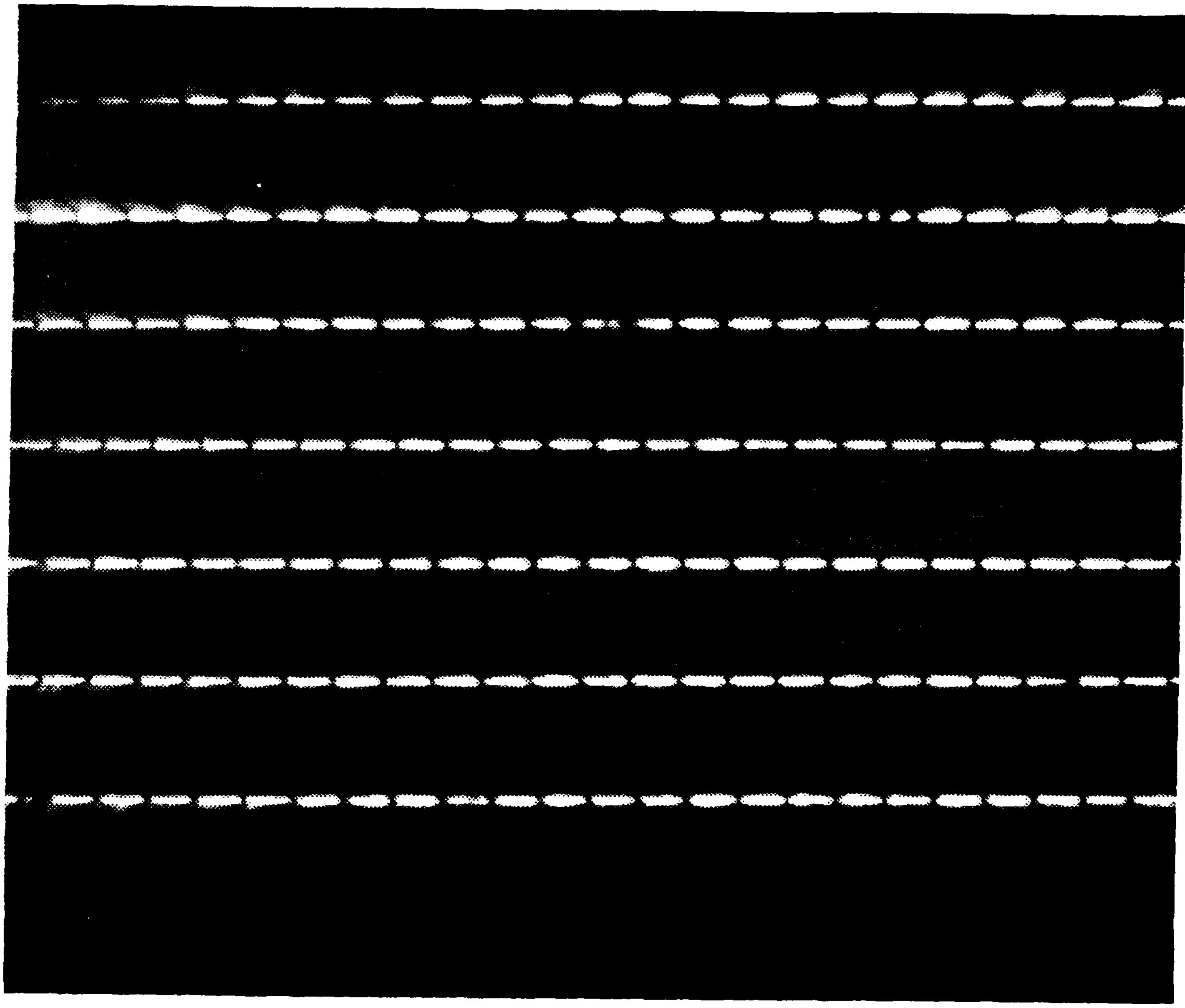

Figure 7. Near field image of a 2D array operating at 30 amps (100 μsec pulses). This image contains only a portion of the entire array (7 bars and 0.25 cm). The camera used to record this image was saturated in spite of the optical density filters (OD=5) used to attenuate the array.

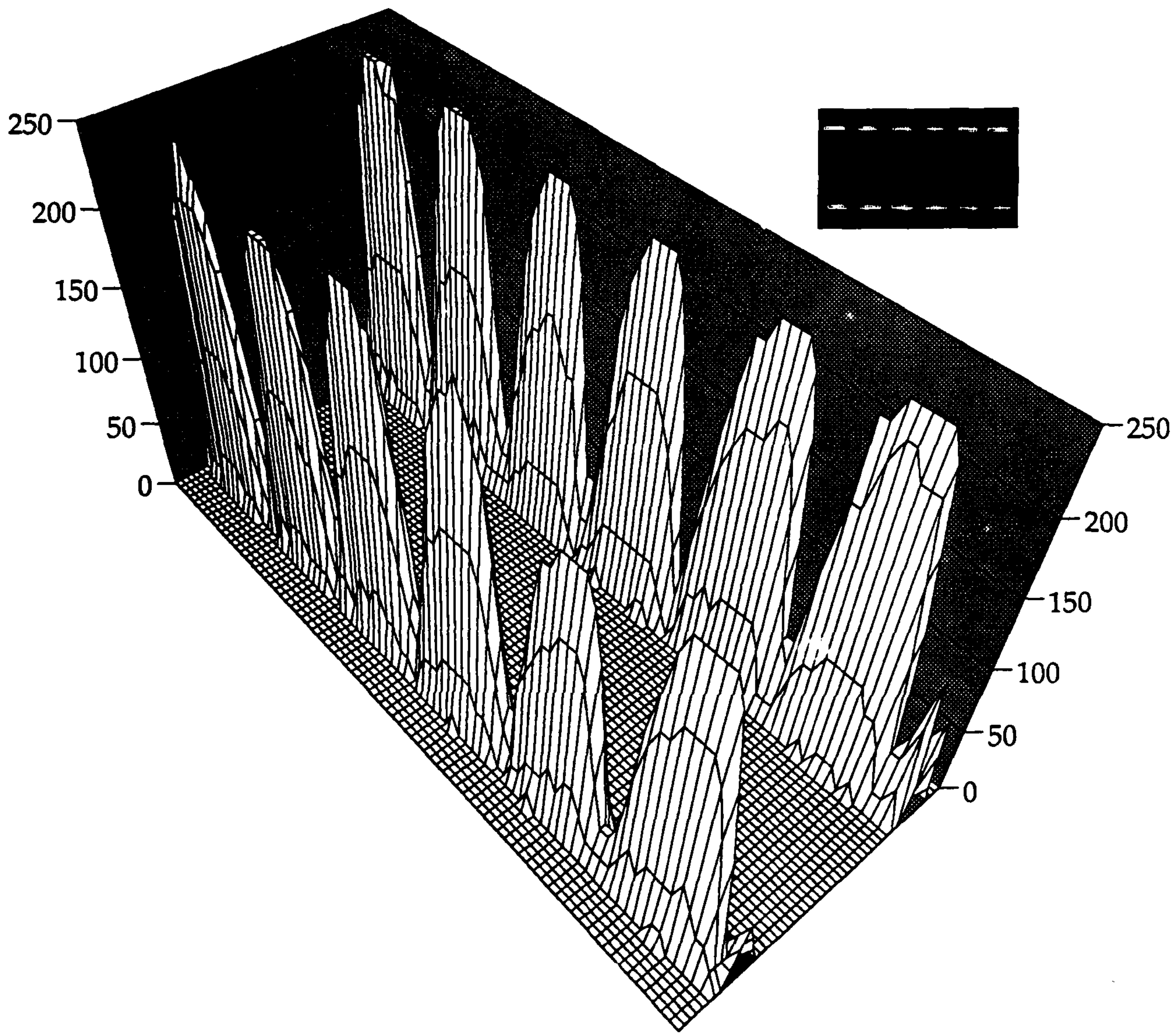

Figure 8. Near field intensity profile of a portion of a 2D array operating at 20 amps (100 μsec pulses). The image used to produce the profile is shown in the inset.

IV. Test Results on Linear Arrays with the New Process

The new process has provided an assembly method for rugged 1 cm linear arrays. Because this process is in the early stages of development, it was decided to apply it to single bar assemblies. The most encouraging feature of the arrays built using the single bar/sub-mount approach is their reliability and maximum current handling capability. Although NSI has not yet performed life tests on these devices, many have survived the testing without apparent degradation. The PI curve and spectra of the 5th array assembled is shown in figure 9.

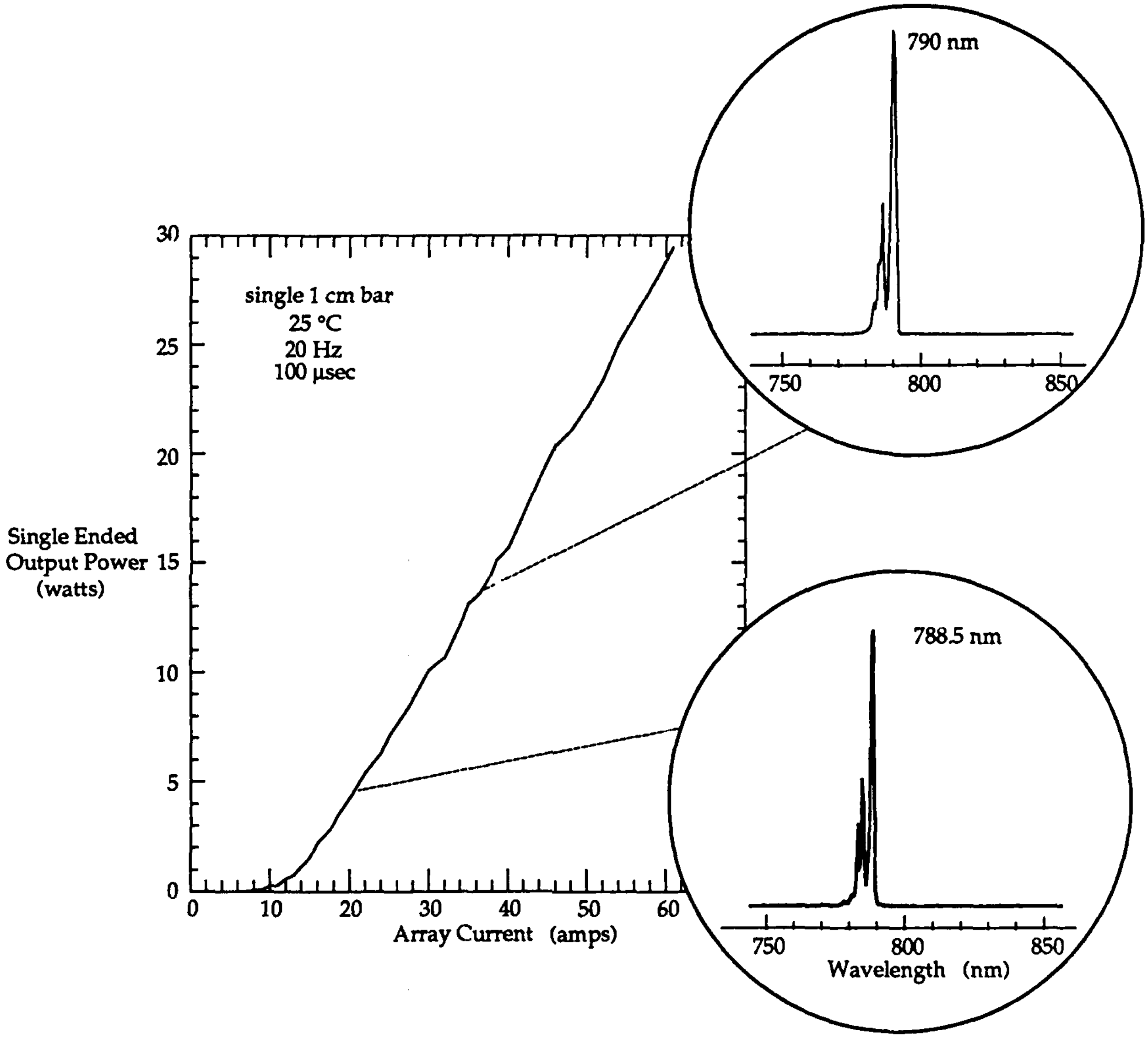

Figure 9. Power versus current and spectra of a linear array assembly operating with 100 μsec pulses at 20 Hz. The bar is uncoated yielded a total output power of 60 watts at 62 amps

Little wavelength shift with current drive or pulse width was observed in these assemblies. Devices have been driven with 100 μsec pulses at currents

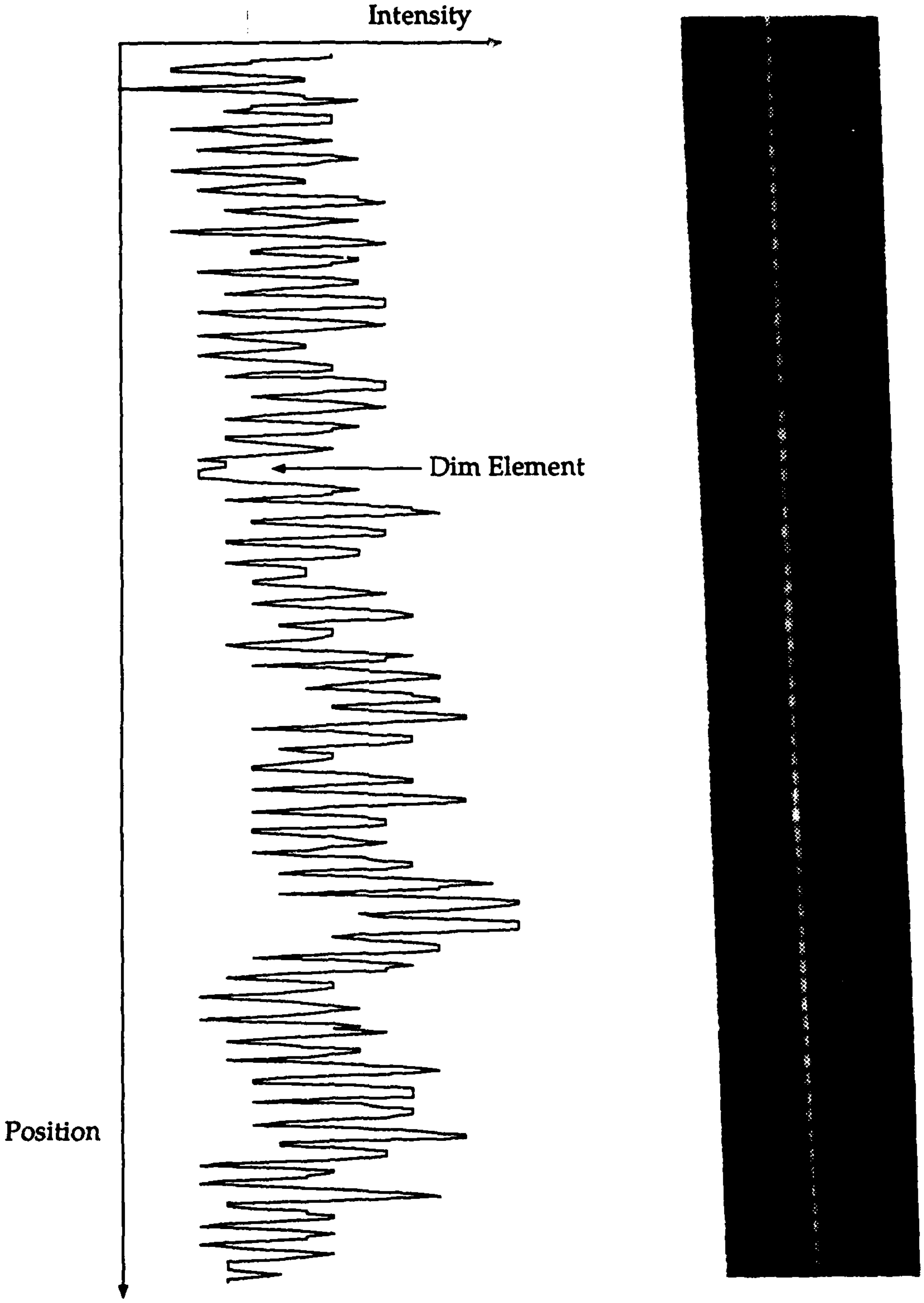

Figure 10. Near field image of an entire linear array operating at 30 amps (100 μsec pulses). The intensity profile across the array is also given.

up to 95 amps (100 emitters/bar) without damage to the array. The highest total output power observed to date was 85 watts at 95 amps. Clearly these linear arrays are superior in every respect to the arrays fabricated in grooves, especially on single bar assemblies. The near field image and profile (taken through the center of the emitting aperture) of a single bar device operating at 30 amps is shown in figure 10. Good uniformity is observed across the entire array with virtually all of the 100 individual emitters active.

V. Facet Coating Results

NSI has developed a working relationship during phase I of this program with Evaporated Metal Films, Inc. (EMF) of Ithaca, N.Y. in the area of laser facet coatings. NSI specified the facet coatings and deposition process to EMF and after several attempts, good results were obtained. A high reflectance stack consisting of 6 quarter wavelength layers of Al_2O_3 and Si.

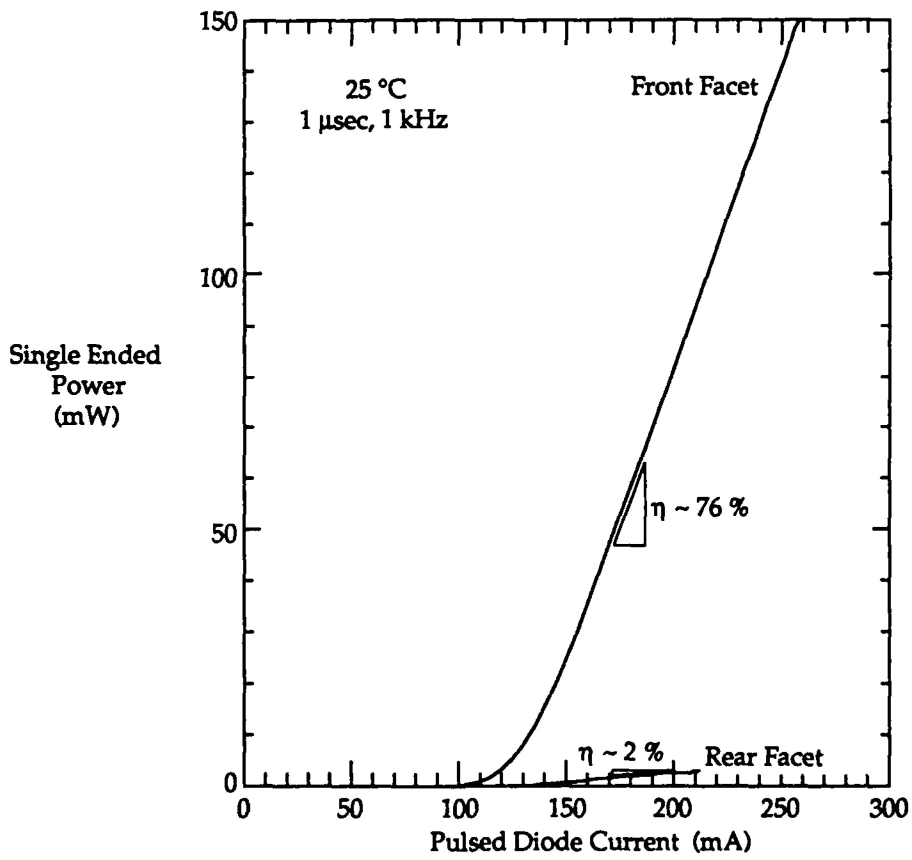

Figure 11. Power versus current measured on a probe facet coated bar on the front and rear facets. The pulse width was 1 μsec at 1 kHz. A deferential quantum efficiency of 76 % was measured on the output facet.

The output facet was coated with a half wavelength coating of SiO_2. Several processed laser bars were held in a fixture and heated to 200 °C prior to the deposition of the coatings. The results of these efforts are shown in figure 11. The coatings resulted in single ended slope efficiencies which exceed 75 %. The front to rear emitted power ratio was in excess of 50. When coated devices such as these are incorporated into a diode array, the conversion efficiency of the array should approach and perhaps exceed 50 %. Presently, fixturing is being developed to provide for large throughput of laser bars in the facet coating process.

VI. Plans for Phase II

It is NSI's intent to submit a phase II proposal to complement an existing phase II program funded by NASA-Langley in a related area. NSI requires additional funding for the development of fabrication technology needed to expand the linear array concept into one for reliable 2D arrays of 1 cm^2 emitting area. In the phase II program, NSI will develop automated life test stations to acquire extended operational data and determine the performance limits for a given device lifetime. The goal of the phase II program is to obtain low cost, reliable 2D arrays of 1 cm^2 emitting aperture at power levels exceeding 2500 Watts for diode pumped solid state laser systems. It is NSI's intent to enter the market place with high performance arrays after phase II of this program.

VII. Summary

In summary, in spite of great difficulties with the originally proposed laser array fabrication scheme, the laser bar in a groove, NSI developed 10 bar diode arrays emitting total powers approaching the 500 watt level. However, the assembly techniques are suspect and the resulting array lifetime was exceedingly poor due to non-uniform thermal distribution across the array. Furthermore, because the assembly places additional demands on the bar fabrication, this method will not be cost effective. An alternative approach was developed which is essentially a modified "Rack & Stack" technique. State of the art results were obtained including 85 watts of total power emitted from a 1 cm laser bar. NSI will aggressively pursue this fabrication technique in a phase II award to result in affordable diode array technology.

VIII. Appendix - List of Phase I Array Assemblies

10 Bar Array Assemblies

ARRAY #	DESCRIPTION SOLDER, # OF BARS	SOURCE MATERIAL	STATUS	MAX POWER	TEST CONDITIONS	WAVELENGTH
MF001	63Sn 37Pb 10 bar	M2413b	FAB. FAILURE	N.A.	PW=100usec	N.A.
MF002	70In 30Pb 10 bar	413b	FAB. FAILURE	N.A.	PW=100usec	N.A.
MF003	70In 30Pb 10 bar	413b	ACTIVE	13.06 W	PW=100usec	808 nm
MF004	70In 30Pb 10 bar	504	TEST FAILURE	N.A.	PW=100usec	N.A.
MF005	70In 30Pb 10 bar	572	ACTIVE	70.32 W	PW=100usec	796 nm
MF006	70In 30Pb 10 bar	572	TEST FAILURE	192 W	PW=100usec	N.A.
MF007	70In 30Pb 1 bar	504	TEST FAILURE	N.A.	PW=100usec	797 nm
MF008	63Sn 37Pb 10 bar	572	TEST FAILURE	N.A.	PW=100usec	N.A.
MF009	63Sn 37Pb 10 bar	413b	TEST FAILURE	24.96 W	PW=100usec	800 nm
MF010	96.5 Sn 3.5 Ag 10bar	413b	TEST FAILURE	N..A.	PW=100usec	N.A.
MF011	63Sn 37Pb 10 bar	572	ACTIVE	64 W	PW=100usec	794 nm
AL001	Cr Au	N.A.	SUBST. FAILURE	N.A.	N.A.	N.A.
AL002	Cr Au	N.A.	SUBST. FAILURE	N.A.	N.A.	N.A.
AL003	Cr Ni Au	N.A.	PROC. FAILURE	N.A.	N.A.	N.A.
AL004	Cr Ni Au	N.A.	PROC. FAILURE	N.A.	N.A.	N.A.
AL005	N.A	N.A.	PROC. FAILURE	N.A.	N.A.	N.A.
AL006	N.A.	N.A.	PROC. FAILURE	N.A.	N.A.	N.A.
AL007	N.A.	N.A.	PROC. FAILURE	N.A.	N.A.	N.A.
AL008	5BAR	N.A.	UNAVAILABLE	100W	N.A.	N.A.
AL009	6BAR	N.A.	UNAVAILABLE	150W	N.A.	N.A.
AL010	8BAR	N.A.	UNAVAILABLE	180W	N.A.	N.A.
AL011	10BAR	D014	TEST FAILURE	180W	N.A.	N.A.
AL012	10BAR	D014	UNAVAILABLE	180W	N.A.	N.A.
AL013	10BAR	M19020473	UNAVAILABLE	223W	PW=200usec	N.A.
AL014	10BAR	M19020473	UNAVAILABLE	200W	PW=200usec	N.A.
AL015	10BAR	M19020473	UNAVAILABLE	216W	PW=200usec	N.A.

Single Bar Arrays (1 cm)

ARRAY NAME	DESCRIPTION SOLDER , #OF BARS	SOURCE MATERIAL	MAX. POWER	STATUS	TEST CONDITIONS
MC3-2	63Sn 37Pb	566	0.032 W	TEST FAILURE	PW=100usec
MC3-4	63Sn 37Pb	566	5 W	TEST FAILURE	PW=100usec
MC3-7	63Sn 37Pb	566	6 W	ACTIVE	PW=100usec
MC4-3	70In 30Pb	572	8.096 W	TEST FAILURE	PW=100usec
MC4-5	70In 30Pb	572	9 W	TEST FAILURE	PW=100usec
MC4-8	63Sn 37Pb	572	20.9 W	FAB. FAILURE	PW=100usec
MC4-9	63Sn 37Pb	572	23.216 W	ACTIVE	PW=100usec
MC5-1	63Sn 37Pb	572	2.74 W	TEST FAILURE	PW=100usec
MC5-3	25In 75Pb	572	31.68 W at 68A	TEST FAILURE	PW=100usec
MC5-4	25In 75Pb	572	34W AT 62A	TEST FAILURE	PW=100usec
MC5-5	25In 75Pb	572	38W at 80A	ACTIVE	PW=100usec
MC5-6	25In 75Pb	573	41.36W at 90A	ACTIVE	PW=100usec